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AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

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REPORT

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5 Pollux Drive
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Standard Form 298 (Rev. 8-98)
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21 separate items enclosed

MEMORANDUM FOR PR (In-House Contractor/In-House Publication)
FROM: PROI (TI) (STINFO)

01 Mar 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-040**
Strakey, P.A., Talley, D.G., Tseng, L.K. (Boeing), Miner, K.I. (Boeing), "The Effects of LOX Post Biasing
on SSME Injector Wall Compatibility"
4th International Symposium on Liquid Space Propulsion (Statement A)
Lampoldshausen, Germany, 13-15 Mar 2000 (Absolute Deadline: 09 Mar 2000)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement,
b.) military/national critical technology, c.) export controls or distribution restrictions,
d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments: _____

Signature _____ Date _____

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release
and/or b.) possible higher headquarters review.

Comments: _____ Prior Release Authorization (PAS-99-044) _____

Signature _____ Date _____

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended,
b.) appropriateness of distribution statement, c.) military/national critical technology, d.) economic sensitivity,
e.) parallel review completed if required, and f.) format and completion of meeting clearance form if required

Comments: _____

Signature _____ Date _____

4. This request has been reviewed by PR for: a.) technical accuracy, b.) appropriateness for audience, c.)
appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/
national critical technology, and f.) data rights and patentability

Comments: _____

APPROVED/APPROVED AS AMENDED/DISAPPROVED

ROBERT C. CORLEY (Date)
Senior Scientist (Propulsion)
Propulsion Directorate



The Effects of LOX Post Biasing on SSME Injector Wall Compatibility

P. A. Strakey and D. G. Talley

Air Force Research Laboratory, Edwards AFB, CA

L. K. Tseng and K. I. Miner

Rocketdyne Propulsion & Power, The Boeing Company,
Canoga Park, CA

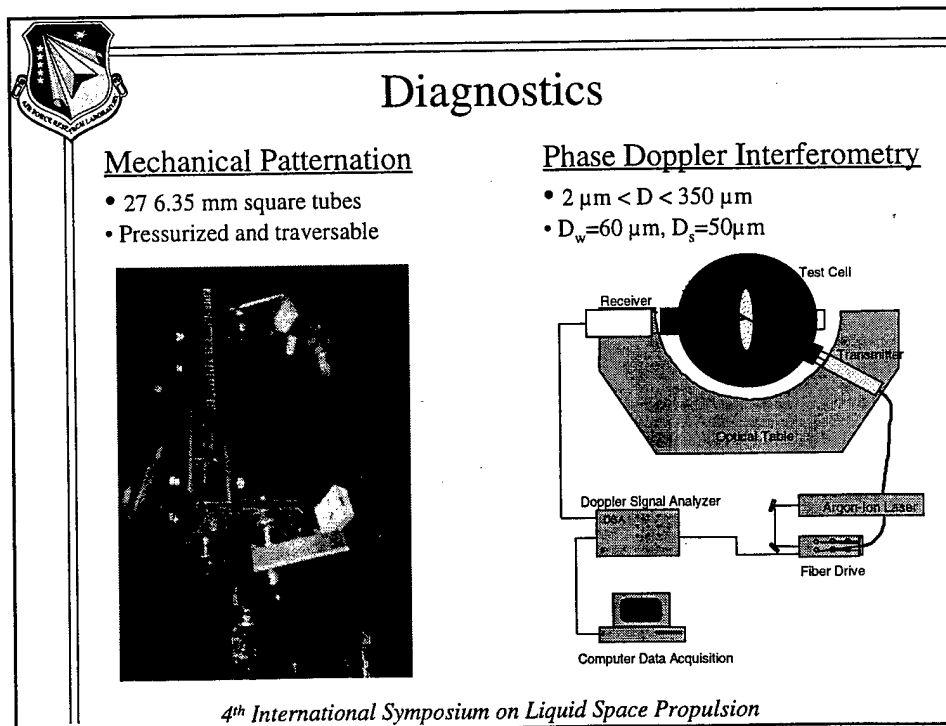
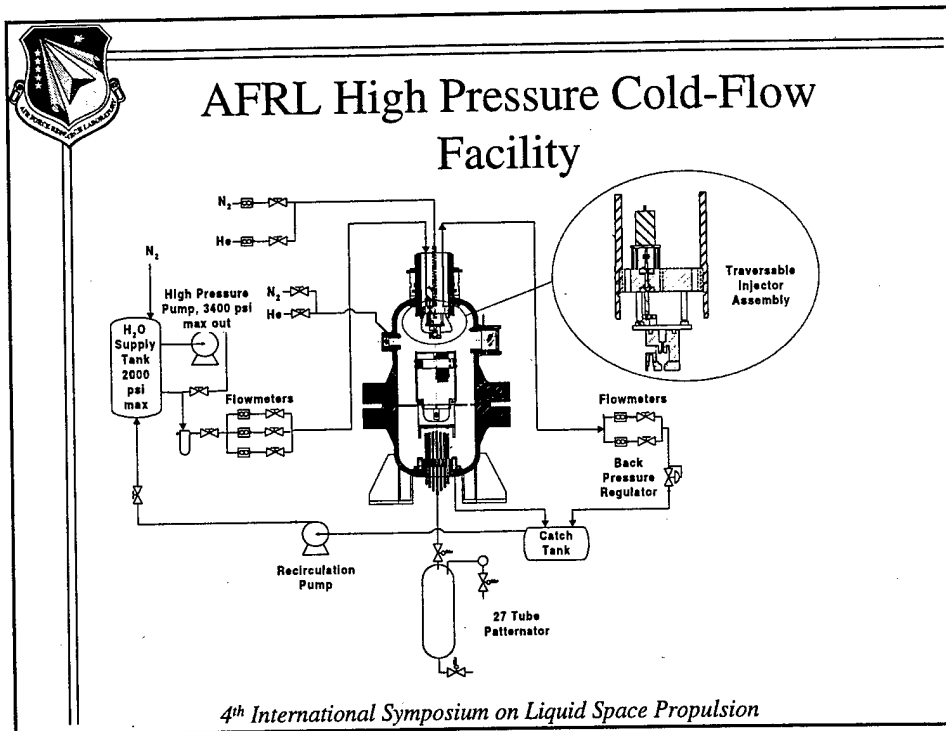
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Motivation

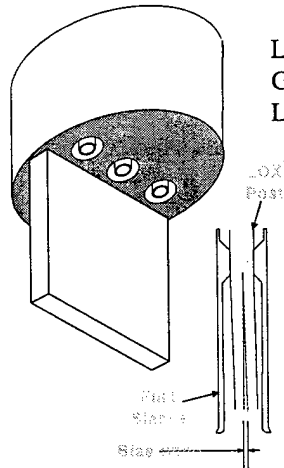
- High efficiency engines require high chamber pressure and throughput.
- Problems;
 - High Heat Flux
 - Oxidative Attack (LOX).
- Wall protection methods;
 - Film Cooling
 - Mixture Ratio Biasing
 - LOX Post Biasing
- The result is Isp loss due to MR non-uniformity in the engine.
- Goal : Provide a detailed understanding, through cold-flow simulations of the effects of LOX post biasing on the liquid and gas phase distribution near a wall.

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Scaling Parameters



LOX Post ID=4.77 mm
Gas Gap=2.24 mm
LOX Post Recess=6.35 mm

Parameter	SSME (LOX/gH ₂ +H ₂ O)	Cold-Flow (H ₂ O/gN ₂)
Pc (MPa)	19.3	0.74
Liq. Vel. (m/s)	31.3	10.0
Den. Ratio(l/g)	117.6	117.6
Vel Ratio (l/g)	0.087	0.087
Mom Ratio (l/g)	0.286	0.286
Mix Ratio (l/g)	3.25	3.25
Liq. Re #	1.1e ⁶	4.3e ⁴

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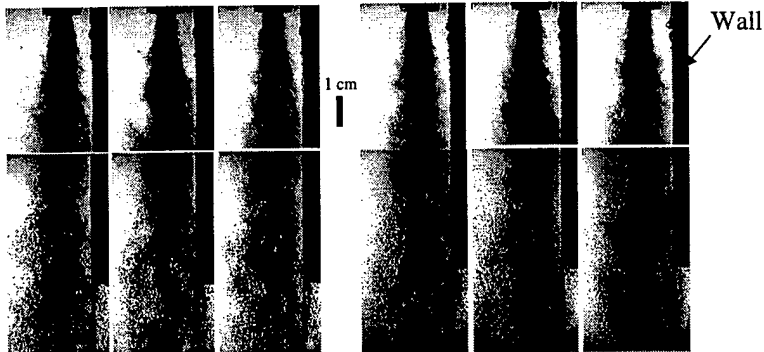


Strobelight Imaging

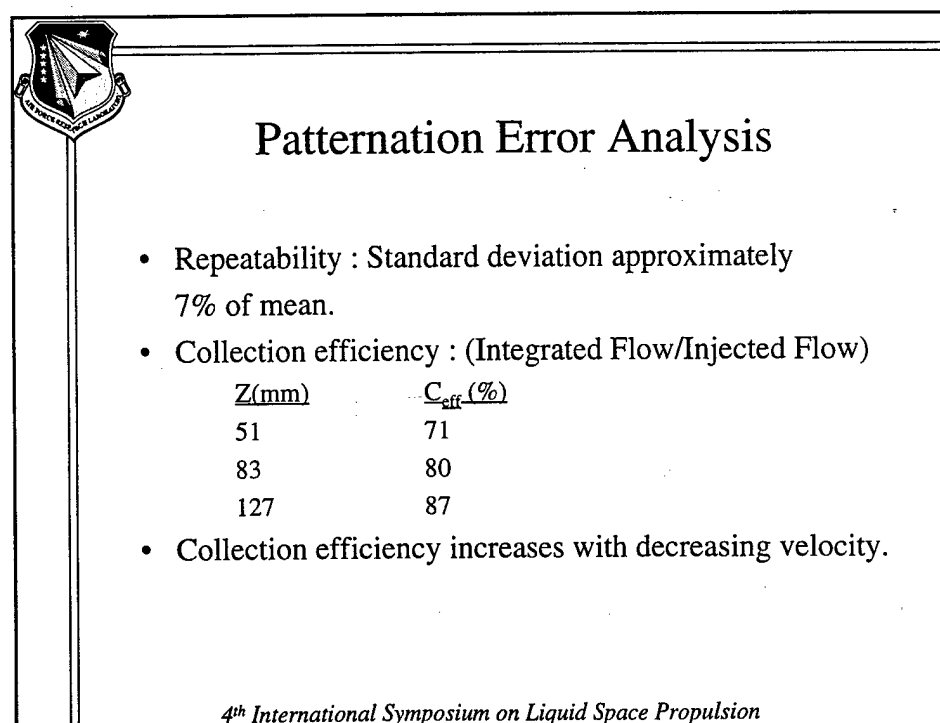
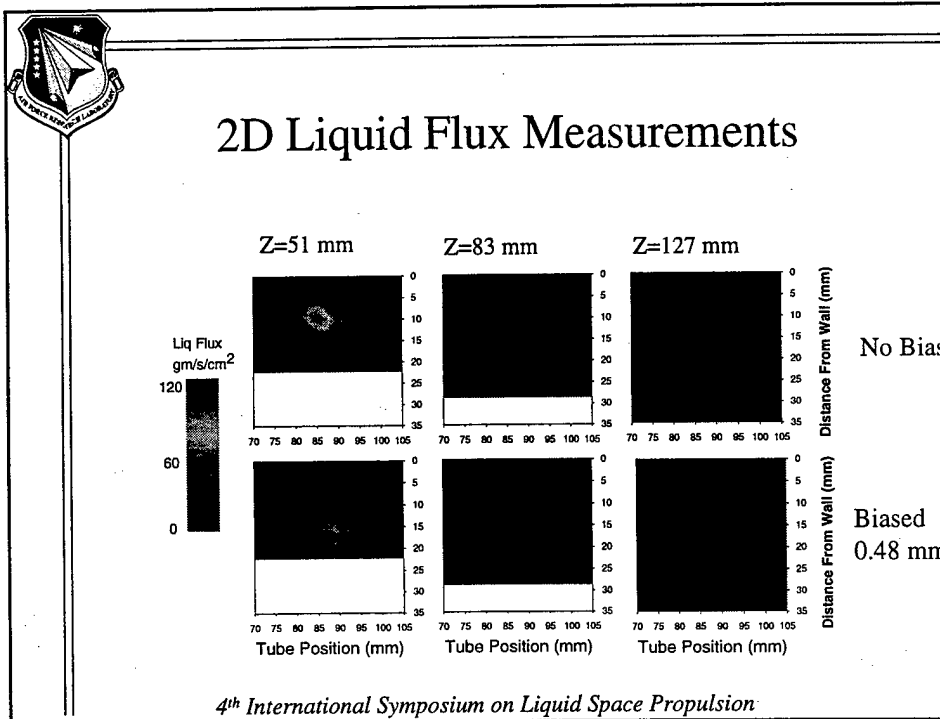
- Biasing shifts the liquid flow away from the wall.

Unbiased
Z = 0 - 45 mm (top row)
Z = 45 - 110 mm (bottom row)

Bias 10 mm
Z = 0 - 45 mm (top row)
Z = 45 - 110 mm (bottom row)



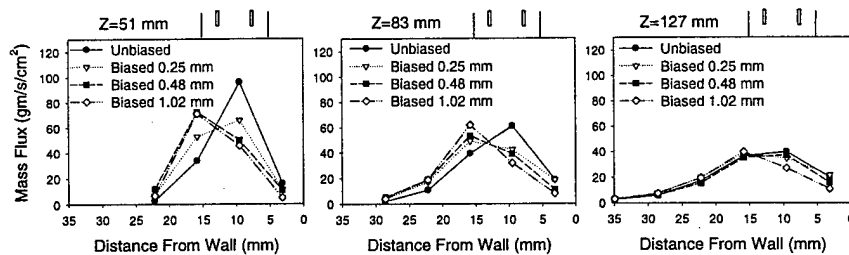
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Liquid Flux Radial Profiles

- Biasing more than 0.48 mm does not increase liquid displacement from wall at $Z=51$ mm.
- Overall effect of biasing decreases with increasing axial distance. Effect near wall persists even at $Z = 127$ mm.

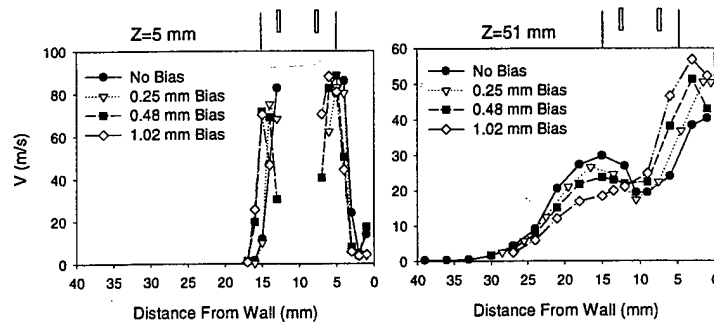


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Gas Phase Velocity

- Very little difference in velocity near injection point ($Z=5$ mm).
- Velocity gradient increases with increasing LOX post bias at $Z=51$ mm.

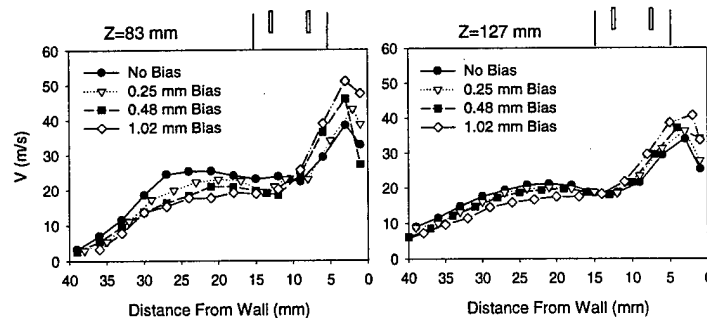


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Gas Phase Velocity

- Effects of LOX post biasing diminish with increasing axial location.

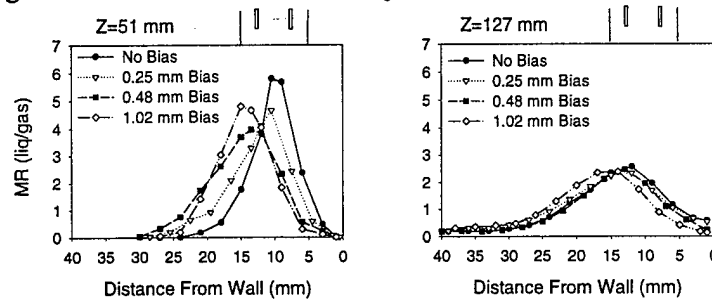


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Mixture Ratio Profiles

- Mixture ratio distribution is "shifted" away from the wall with LOX post biasing.
- The shift is due to a combined result of the displacement in liquid distribution away from the wall and an increase in gas flow on the wall side of injector.



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Heat Flux Analysis

- Method 1 : Flat plate turbulent correlation:

$$q'' = 0.0296 \text{Re}_z^{\frac{4}{5}} \text{Pr}^{\frac{1}{3}} \frac{k_g}{Z} (T_g - T_w)$$

$$\text{Re}_z = \frac{V_g \rho_g Z}{\mu_g}$$

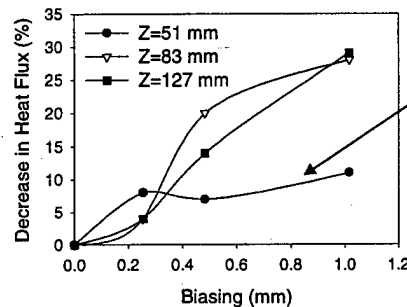
- Gas velocity from cold-flow data
- T_g , μ_g , k_g , Pr_g , ρ_g from equilibrium calculations at local MR.
- $T_w = 600 \text{ K}$
- q'' averaged over the thermal boundary layer (6 mm).

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Heat Flux Analysis (Method 1)

- Gas-Gas studies have shown a similitude between cold-flow data and hot-fire data at equivalent residence times.
- For the SSME, $\tau = 1 \text{ ms}$, approximately equivalent to the 51 mm cold-flow data.



$$q'' \propto V^{0.8} \cdot T_g$$

$$T_g = f(\text{MR})$$

$$\text{As } V \uparrow \quad T_g \downarrow$$

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Heat Flux Analysis (Method 2)

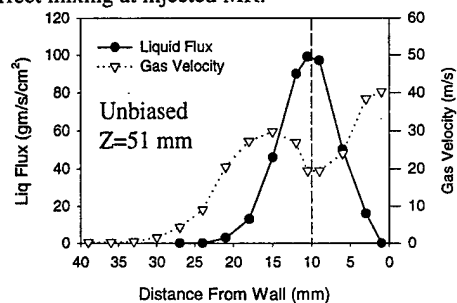
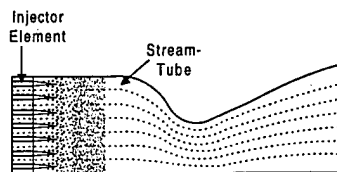
- Use sub-scale calorimeter test data as a base-line case for unbiased condition.
- Adjust q'' axial profile using flat plate correlation accounting for increased gas flow with biasing ($Z=51$ -127 mm).
- Extrapolate adjusted q'' profile to throat.
- Result : Heat load reduced by 7.1% with 0.48 mm biasing
 - Agrees very well with full-scale engine test data.

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Performance Analysis

- Streamtube analysis
 - Engine consists of 515 “core” elements and 85 “wall” elements.
 - Assumes no mixing between adjacent elements.
 - Each wall element subdivided into 2 halves defined by peak of liquid flow distribution.
 - $I_{sp} \text{ total} = \sum m_p \cdot I_{sp}$
 - Unbiased represents case of perfect mixing at injected MR.

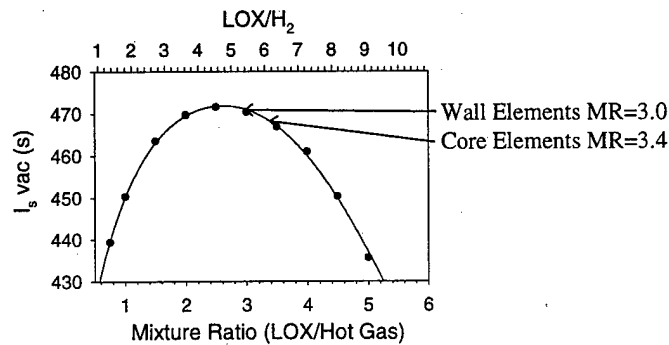


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Performance Analysis

- Vacuum Isp from equilibrium calculations.
- Oxidizer : LOX @ 122K
- Fuel : 55% H_2 +45% H_2O @ 800K
- $P_c=2870$ psi, $A_e/A_t=69.1$

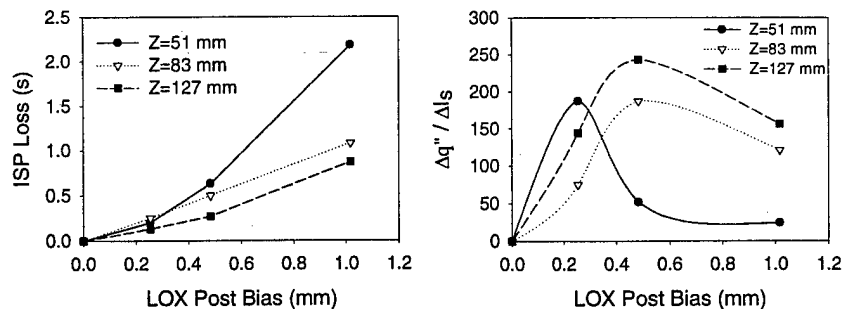


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Performance Analysis

- ISP loss for SSME (Bias=0.48 mm) between 0.3 and 0.6 s.
- $\Delta q''/\Delta Isp$ optimized at a Bias between 0.25 and 0.48 mm.

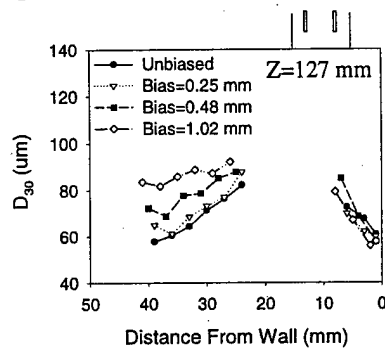


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Droplet Sizing

- Droplet size measured with PDI technique.
- D_{30} is inversely proportional to gas velocity.
- Combustion efficiency is believed to be mixing limited, weak dependency on droplet size.



Data only shown where validation rates were high and mass flux agreement was good.

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Conclusions

- LOX post biasing results in displacement of liquid flow away from the wall, and higher gas velocity near wall. Net result is a decreased MR near the wall.
- Isp loss increases with increasing LOX post bias.
- Some reduction in bias could recover a small amount of Isp, while still providing adequate wall protection.
- Optimization curves can aid injector designers in choosing a level of biasing.
- Droplet size should not play a large role.

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MEMORANDUM FOR THE PROPULSION DIRECTORATE

FROM: Peter Strakey, PRSA

SUBJECT: Request For Release of In-House and Contractor Technical Information

1. The attached item, summarized below, is information generated from data produced by, for, or under contract to Air Force Research Lab's Propulsion Directorate. (Author or Project Manager)

Author(s): P. A. Strakey and D. G. Talley (AFRL) & L. K. Tseng and K. I. Miner (Boeing, Rocketdyne Division)

Title: "The Effects of LOX Post Biasing on SSME Injector Wall Compatibility"

Source: In-House Project (AF 6.1/6.2/6.3) / Contract # _____ / Other _____ SBIR (Y/N)

JON: 3058RF9A Project Mgr/Div/Ext: Doug Talley/PRSA/5-6174

Release Format: Abstract / Paper / Oral Presentation / Slides / Poster Session / Tech Report / Other

Security Classification: Unclassified

If classified, classified by _____

Declassify on _____

Disclosure: Public Release / Limited Release/Foreign Release (See Table) Public Release

Forum/Audience: 1999 Joint Propulsion Conference

AIAA Paper 99-2888

Meeting Location and Date: Los Angeles, CA, June 20-24, 1999

Submission Deadline: NA

Prior Release Authorization (insert PA #): _____ Date: _____

STINFO tracking number: AFRL-PR-ED-TP-FY99-0074 Date assigned: 29 Mar. 1999

2. The attached material has been independently reviewed for sensitivity and classification.
(Author/Project Manager and Reviewer)

a. Material is technically accurate ✓ accurate as amended _____ Initial: AS

b. The following Distribution Statement is appropriate for this item: _____ Initial: AS
(AFI 61-202, AFI 61-204, OPRs: STINFO and FDO)

c. Material IS / IS NOT identified as a Military/National Critical Technology. Initial: AS
(AFI 61-204, OPR: STINFO and FDO)

d. Material IS / IS NOT subject to export controls or distribution restrictions. Initial: AS
(AFI 61-204, OPRs: STINFO and FDO)

The Effects of LOX Post Biasing on SSME Injector Wall Compatibility

P.A. Strakey and D.G. Talley
Air Force Research Laboratory, Edwards AFB, CA

&

L.K. Tseng and K.I. Miner
Boeing Rocketdyne Division, Canoga Park, CA

Abstract

An experimental investigation has been carried out to examine the effects of LOX post biasing of a shear coaxial injector on the behavior of the spray near a chamber wall. The experimental work was performed with inert propellant simulants in a high-pressure chamber. Injector flow rates and chamber pressure were designed to match the Space Shuttle Main Engine (SSME) injector gas-to-liquid density and velocity ratio at the point of propellant injection. Measurements of liquid mass flux, gas phase velocity and droplet size were made using mechanical patternation and phase Doppler interferometry techniques. The measurements revealed that the liquid mass flux distribution shifts away from the wall with increasing LOX post bias away from the wall. The shift in the liquid flux distribution was much greater than that caused by the angling of the LOX post alone. Gas velocity near the wall simultaneously increased with increasing LOX post bias away from the wall. The increase in wall side gas velocity was due to the higher fraction of gas injected on the wall side of the injector as a result of the eccentricity at the injector exit. The net result is a decrease in mixture ratio near the wall. Estimates of heat transfer and engine performance relative to the unbiased case are presented.

Introduction

The thrust of rocket propulsion technology today is to reduce engine costs while maintaining engine life and performance. One area of potential improvement in propulsion efficiency and engine lifetime is injector wall compatibility. In an effort to increase engine performance, chamber pressures have historically been increasing. The rate of heat transfer from the hot combustion gases to the chamber wall is proportional to chamber pressure and in many cases results in a chamber wall temperature that is unacceptably high using regenerative cooling alone. This results in a need for additional wall cooling which is typically accomplished by increasing the fuel flow near the inside wall of the combustion chamber. The increased fuel flow reduces the mixture ratio near the wall, thereby decreasing the temperature of the combustion gases. The increased fuel flow also provides a protective barrier against oxidizer attack on the chamber wall.

A number of methods have been developed and successfully implemented to provide gas or liquid film cooling protection for the combustion chamber wall. A commonly used method is the introduction of a row of holes in the injector faceplate very close to the chamber wall. These holes provide a curtain of protective film coolant, which can be either gaseous or liquid in phase. This technique can be applied to almost any type of injector configuration and has been used successfully for years in many LOX/kerosene impinging injector engines.

Another method of wall cooling which is particularly applicable to coaxial types of rocket injectors involves operating the outer row of injectors at a reduced mixture ratio either by increasing the fuel flow or by decreasing the oxidizer flow. The lower mixture ratio decreases the temperature of the combustion products near the wall. This is one type of wall protection that is employed in the SSME, which uses LOX/gH₂ shear coaxial injection elements. Another form of wall protection used in the SSME is the angling or "biasing" of the outer row of LOX posts inward, away from the combustion chamber wall. The biasing of the LOX post creates an eccentricity of the fuel annulus providing for a larger flowrate of

gaseous fuel on the outer side of the injector. This arrangement, in conjunction with the decreased mixture ratio for the outer row elements has been proven to provide adequate wall protection.

The price that is paid for protecting the wall by these methods is a loss in specific impulse (I_s) due to deviation in mixture ratio near the wall of the combustion chamber. It has been shown in a number of theoretical and experimental studies that any digression from the average mixture ratio in a combustion chamber results in a loss of performance, as measured by I_s [1,2]. This is true even when the overall engine mixture ratio is not at the optimum mixture ratio for maximizing I_s , as long as the I_s versus mixture ratio curve is parabolic or similar in shape. This is the case with hydrogen and oxygen and most other propellant combinations. The sensitivity of performance to mixture ratio distribution in the combustion chamber is due to the relatively poor rate of mixing in the radial direction as a result of high axial acceleration rates of the combusting propellants, and short chamber lengths in comparison to the chamber diameter.

A study has been conducted at the Air Force Research Laboratory (AFRL) high-pressure cold-flow facility to increase the understanding of the injector wall interaction of a SSME shear coaxial injector. The goal was to provide a detailed understanding, through cold-flow simulations, of the effects of LOX post biasing on the liquid and gas phase distribution near a wall. Understanding the effects of LOX post biasing on the spray characteristics will allow injector designers to minimize the performance loss while still providing adequate wall protection.

Experimental Setup

Water and gaseous nitrogen were used as simulants for LOX and gaseous hydrogen. In order to simulate the conditions inside the actual engine, the tests were performed at elevated pressure and at flow rates which match the hot-fire injection gas-to-liquid density and velocity ratios. Spray characteristics which were measured include liquid mass flux distribution, gas phase velocity and droplet size.

The experimental facility is capable of characterizing full scale single element rocket injectors in cold flow at pressures to 13.8 MPa. Water, which is used as a simulant for liquid oxygen, is stored and pressurized in a 1 m³ tank. Nitrogen is stored in a 6 m³ tank at 40 MPa. The injector gas and liquid flow rates are controlled with throttling valves and measured with turbine flow meters to an accuracy of +/- 1%. Chamber pressure is measured to within +/- 0.5%. The maximum water flow rate is 1.8 kg/s and the maximum nitrogen flowrate is 0.18 kg/s. The chamber consists of a 0.5 m diameter stainless steel, optically accessible pressure vessel containing a 27 tube linear array mechanical patternator which can be traversed through the spray. The patternator tubes are 6.35 mm square in dimension. A mechanical shutter prevents liquid from entering the tubes until the spray conditions are obtained at which time the shutter is

opened and liquid is collected for a specified amount of time in a series of stainless steel bottles connected to the patternator tubes. After the shutter has closed, the bottles are de-pressurized and the liquid is emptied into beakers and weighed. The mass flux is simply the mass of collected fluid divided by the collection time and cross sectional area of the collection tubes. The patternator was traversed through the spray at 6.35 mm steps, thus yielding a two-dimensional map of the liquid mass flux distribution.

Three 50-mm and one 120-mm sapphire windows provided optical access to the chamber for spray imaging and for droplet size and velocity measurements using phase Doppler interferometry (PDI).

The injector, which was designed and manufactured by Rocketdyne, consists of a stainless steel manifold containing three SSME fuel sleeves and LOX posts. The

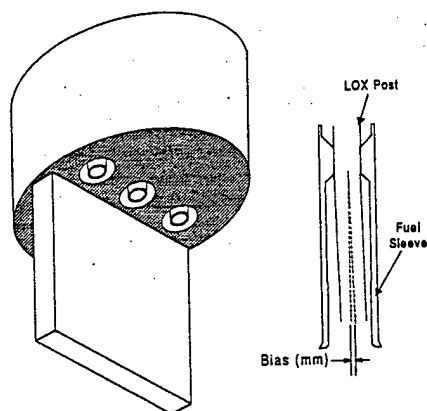


Figure 1: Schematic of the 3-element SSME injector and wall test article along with a cutaway of an injector element.

what about momentum ratios?

✓ spreadsheet
✓ 073MEMORANDUM FOR PRR ^{In-House/} (Contractor Publication)

FROM: PROI (TI) (STINFO)

22 April 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0074
Strakey, Talley, et. al. "The Effects of LOX Post Biasing on SSME Injector Wall Compatibility"

AIAA Joint Propulsion Conference

(Public Release)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments:

Appropriate for Public Release

Signature

[Signature]

Date

9 May 99

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b.) possible higher headquarters review.

Comments:

OK to release

Signature

[Signature]

Date

5/8/99
[Signature]

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended, b.) appropriateness of distribution statement, c.) military/national critical technology, d.) economic sensitivity, e.) parallel review completed if required, and f.) format and completion of meeting clearance form if required

Comments:

format ok, references ok, minor editing marked on text.

Signature

Nancy G. Chalfant

Date

4 May 99

4. This request has been reviewed by PRR for: a.) technical accuracy, b.) appropriateness for audience, c.) appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/national critical technology, and f.) data rights and patentability

Comments:

CC: PAO
FDO

PRSA (Talley)

PRSA (Strakey)

APPROVED/APPROVED AS AMENDED/DISAPPROVED

[Signature]
ROBERT C. CORLEY

Senior Scientist (Propulsion)
Propulsion Directorate

(Date)

18 May 99

manifold provides separate inlet ports for gas and liquid delivery. A wall was mounted on the face of the manifold at 6.35 mm from the outside edge of the fuel sleeves to simulate the presence of the combustion chamber wall. The LOX posts had an internal diameter of 4.77 mm and the fuel gap annulus was 2.24 mm with the LOX post centered in the annulus. Figure 1 is a schematic of the injector manifold along with a cross sectional view of one of the injector elements. The LOX post was biased by angling the post away from the wall. Bias was measured as the displacement of the tip of the LOX post from the unbiased condition.

Injector Scaling Parameters

Chamber pressure and flow rates were chosen to match the following SSME injector hot fire similarity parameters at the point of injection: gas-to-liquid velocity ratio, density ratio, momentum ratio and mixture ratio, while the maximum gas flowrate was limited by the maximum facility flowrate. Table 1 contains the single element run conditions used in this study along with conditions for the SSME at full power level. The most notable difference between cold-flow and the SSME hot-fire conditions was the lower liquid Reynolds number for the cold-flow tests, which was lower by a factor of 25 due to the lower injection velocity and a seven-fold higher viscosity for water. The results should still provide qualitative information on spray behavior because the Reynolds number for the cold-flow tests was still well into the fully turbulent regime. For all of the results presented here, all three injectors were flowing gN_2 at the flow rate specified in Table 1, however, water was flowed through only the central injector. This was an effort to reduce the optical thickness of the spray field in order to facilitate the droplet size and velocity measurements. The gas flow in the outer two injectors was designed to simulate the aerodynamic confinement encountered in the actual engine.

Table 1 : Scaling parameters for cold-flow and engine operating conditions.

Parameter	SSME (LOX/ gH_2+H_2O)	Cold-Flow (H_2O/N_2)
Chamber Pressure (MPa)	19.3	0.74
Liquid Flowrate (kg/s)	0.63	0.18
Liquid Injection Velocity (m/s)	31.3	10.0
Liquid Density (kg/m ³)	1117	1002
Liquid Reynolds Number	1.1×10^6	4.3×10^4
Gas Flowrate (kg/s)	0.193	0.056
Gas Injection Velocity (m/s)	360.6	115.9
Gas Density (kg/m ³)	9.47	8.48
Gas Reynolds Number	9.0×10^5	2.4×10^5
Density Ratio (liq/gas)	117.6	117.6
Velocity Ratio (liq/gas)	0.087	0.087
Momentum Ratio (liq/gas)	0.286	0.286
Mixture Ratio (liq/gas)	3.25	3.25

Strobelight Imaging

Spray imaging experiments were conducted at a variety of test conditions using a 5- μs duration strobelight to back-light the spray and a CCD camera and VCR to capture and store images of the spray. These images yielded qualitative information on the shape of the sprays. A series of images were taken at the conditions listed in Table 1 for an unbiased injector and for a biasing of 0.48 mm away from the wall. The images show the spray from the edge on and span an axial distance of 0 to 45 mm (top row) and 45 to 110 mm (bottom row). Note that each image in the top and bottom row series of images was captured at a different instant in time and are therefore representative of typical spray behavior. The dark areas on the image are areas with a high liquid concentration. These images indicate that biasing the LOX post tended to shift the liquid flow away from the wall.

5- μs

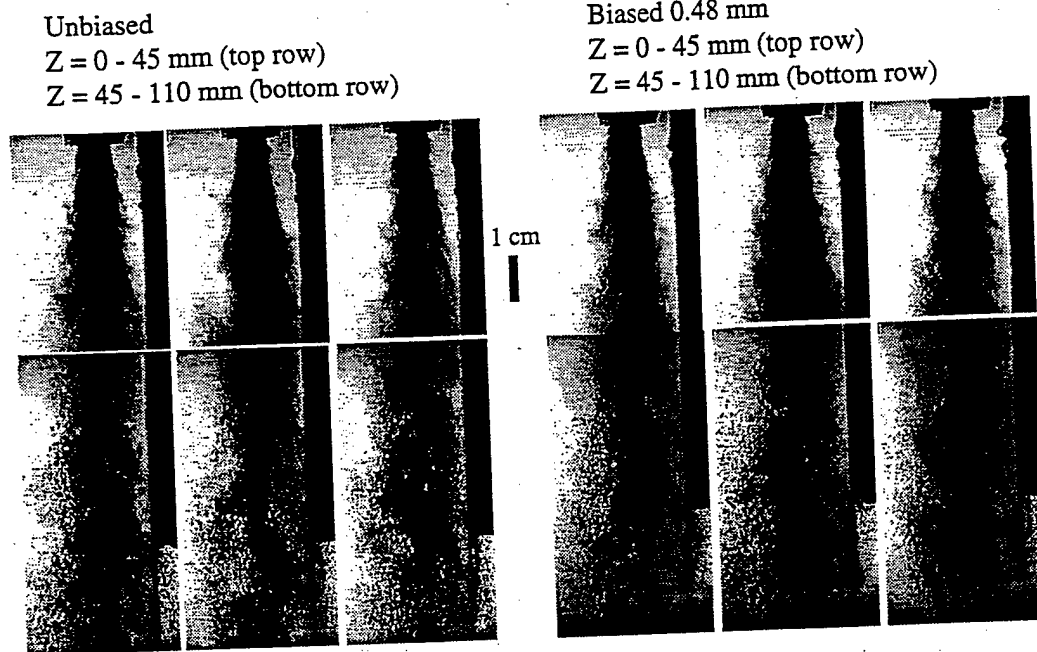


Figure 2: Strobe back-lit images of the unbiased injector spray (left) and biased injector (0.48 mm away from wall) spray (right) for two ranges of axial location (0-45 mm top row and 45-110 mm bottom row). The wall is the dark object located on the right hand side of each image. Note that the top and bottom row images were acquired at different times and are only representative of typical spray behavior. Test conditions given in Table 1.

Liquid Mass Flux Results

Mechanical patterning measurements of liquid mass flux were made with all three injectors flowing N_2 and only the central injector flowing water. Tests were conducted with the LOX post un-biased (centered in the fuel sleeve) and with the LOX post tip biased away from the wall 0.25, 0.48 and 1.02 mm. Figure 3 contains contour plots of measured liquid mass flux at axial locations of 51, 83 and 127 mm from the injector exit plane. The wall was located at 0.0 mm and the center of the injector was located at 10 mm from the wall. These results show a decrease in liquid flux near the wall and a shift in the peak mass flux away from the wall as the LOX post was biased away from the wall. The shift in the peak flux was largely due to an increase in gas flow on the wall side of the biased injector, which will be discussed in a later section.

Figure 4 is a plot of liquid mass flux as a function of distance from the wall through the centerline of the spray. The size and location of the injector is shown in the the figure. Figure 4 clearly shows the shift in the peak of the liquid flux distribution away from the wall with increasing LOX post bias. It is interesting to note that the maximum liquid flux displacement occurs for a biasing of 0.48 mm. Further biasing to 1.02 mm did not shift the liquid flux any further away from the wall. Also note that the effect of LOX post biasing diminished with increasing axial distance from the injector.

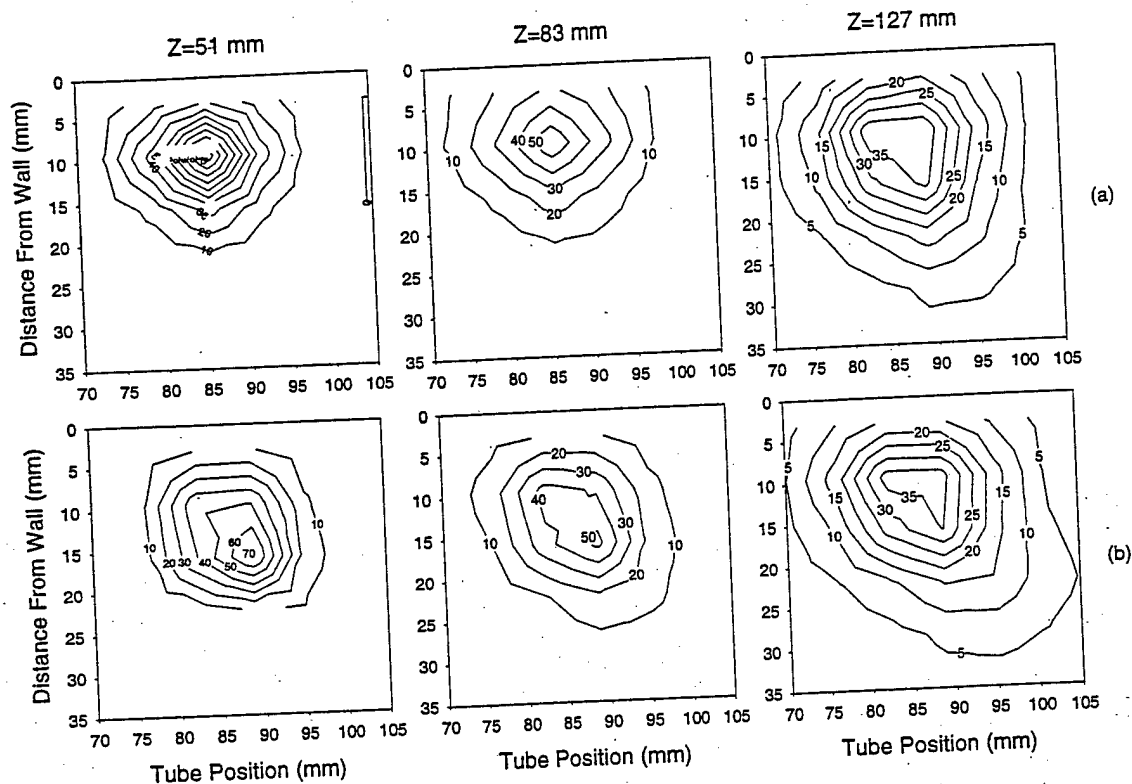


Figure 3: 2-D liquid mass flux distributions at Z=51, 83 and 127 mm, for the test conditions in Table 1 for the (a) unbiased injector and (b) injector biased 0.48 mm away from the wall. The wall is at 0 mm and contours are in gm/s/cm^2 .

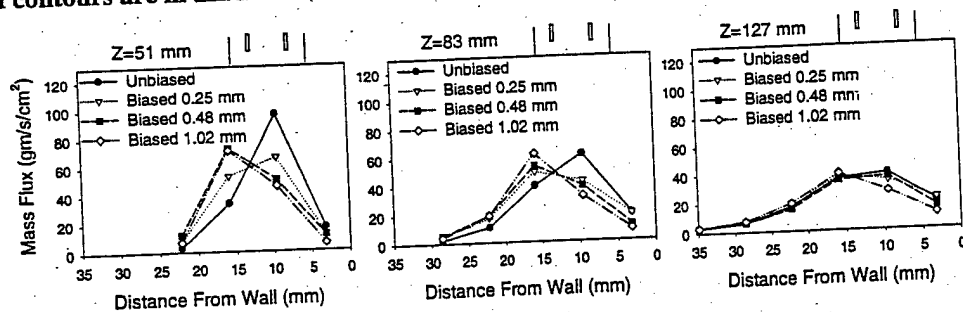


Figure 4: Liquid mass flux distribution through the centerline of the spray as a function of LOX post biasing and axial distance. Run conditions listed in Table 1.

The shift in the peak of the liquid mass flux distribution was much greater than that caused by only the angling of the LOX post. For the case of 0.48 mm bias, the LOX post biasing angle was 0.69° , which would result in a shift of 0.61 mm away from the wall at an axial location of 51 mm. The actual shift in the peak as determined by curve fitting the liquid flux data to a Gaussian profile was 3.9 mm.

Estimation of error

Several repeat runs were made with the injector biased at 0.48 mm in order to assess the repeatability of the liquid mass flux measurements. The error associated with repeatability varied slightly through the spray but the average standard deviation in liquid mass flux was about 7%. Another error associated with mechanical patternation measurements is rejection of droplets at the entrance of the patternator tubes due to the formation of a stagnation zone. The patternator bottles were vented back to chamber to allow the gas that enters the collection tubes to return to the chamber. There was, however, a pressure drop through the patternation system that generates a stagnation zone at the entrance to the patternator tubes. The smaller droplets tend to follow the gas streamlines around the patternator entrance and are not collected. Larger droplets, which carry most of the mass flux in the spray have enough momentum in the axial direction to overcome the streamlines formed by the stagnation zone and enter the patternator. The amount of error associated with droplet rejection can be assessed by integrating the total mass flux over the extent of the spray and comparing to the injected mass flow rate. The result is a collection efficiency, which will always be less than 100%. The measured collection efficiency for the unbiased and biased runs were similar, but varied in the axial direction. The average collection efficiency was 71%, 80% and 87% for the axial locations of 51, 83 and 127 mm, respectively. Collection efficiency increased with increasing axial distance from the injector as the local gas velocity decreased.

Velocity Measurements

Gas phase velocity and liquid droplet size measurements were made with a 2-component phase Doppler interferometer. Measurements were made with the PDI at axial locations of 51, 83 and 127 mm. The PDI was optically configured to measure the smallest droplets possible. It was calculated that droplets less than about 6 μm in diameter would be following the mean flowfield completely as defined by a Stokes number greater than $\frac{10}{\text{ten}}$, and could be used as "seed" particles for making measurements of the gas phase velocity. The Stokes number is defined as;

$$\text{St} = \frac{\tau_F}{\tau_D} \quad (\text{Eq. 1})$$

where τ_F is the time scale of the flowfield and τ_D is the droplet response time which are calculated as follows.

$$\tau_F = \frac{Z}{V} \quad (\text{Eq. 2})$$

$$\tau_D = \frac{\rho_l \cdot D^2}{18 \cdot \mu_g} \quad (\text{Eq. 3})$$

In Equation 2, Z is the minimum distance from the injector and V is the maximum flowfield velocity. At a distance of 51 mm the maximum flowfield velocity was estimated to be 50 m/s from initial experiments. This yielded a time constant of 1.02 ms and a maximum droplet size, D, of 5.7 μm for a Stokes number of $\frac{10}{\text{ten}}$.

Measurements were also made as close as 5 mm from the injector face, but there were very few droplets available for making velocity measurements here. Therefore, the gas stream being fed to the injector was seeded with a dilute spray of very small droplets to act as tracer particles. The introduction of droplets to the gas flow was far enough upstream of the injection point to ensure that the droplets were following the flowfield.

The PDI was configured with a 500-mm focal length transmitter and receiver lens. A 60 μm beam waist and a 50 μm slit were used in order to facilitate measurements in the anticipated high number density sprays. A ten-to-one intensity validation scheme was implemented to reject erroneous measurements associated with the relatively small beam waist in comparison to the droplet sizes being measured ($2 < D < 350 \mu\text{m}$) [3].

60- μm

The PDI was fixed in location with respect to the chamber windows and the injector was traversed through the probe volume at 1-mm steps for the axial location of 5 mm and 3-mm steps for all other axial locations. This yielded a radial profile of the gas phase velocity and droplet diameter from the outside edge of the spray to the wall, through the centerline of the spray as defined by the center of the LOX post. At each location in the spray, 5000 measurements were recorded. Velocities are reported as the average velocity of droplets less than 6 μm in diameter. It was found, however, that there was very little correlation between droplet size and velocity, indicating that velocity was independent of droplet size.

Figure 5 contains plots of gas phase axial velocity as a function of distance from the wall at axial locations of 5, 51, 83 and 127 mm for the test conditions listed in Table 1. The relative size and location of the injector is shown on each plot. Figure 5 shows that near the exit of the injector ($Z=5$ mm) the gas phase velocity was only slightly higher on the wall side of the injector than the far side of the injector. Note that at the axial location of $Z=5$ mm, no data is shown in the center of the spray. This is due to the fact that at this axial location the liquid core of the spray was still intact and data validation rates at these locations were very low. Further downstream from the injection point the gas phase axial velocities were much higher on the wall side of the spray than the far side of the spray. This is because the spray was physically confined by the presence of the wall at 0 mm and was aerodynamically confined by the injectors operating on either side of the spray. The far side of the spray was not confined and was free to expand, thus resulting in a lower velocity.

The most interesting feature of Figure 5 is the increase in velocity near the wall with a corresponding decrease in velocity on the far side of the spray for the runs with the LOX post biased away from the wall. The ratio of wall side velocity to far side velocity increased with increasing LOX post bias. The velocity gradient was caused by the unequal exit areas of the gas annulus at the injector exit, with a larger flow area on the wall side of the injector. Since the flow was physically confined on the wall side of the injector, the

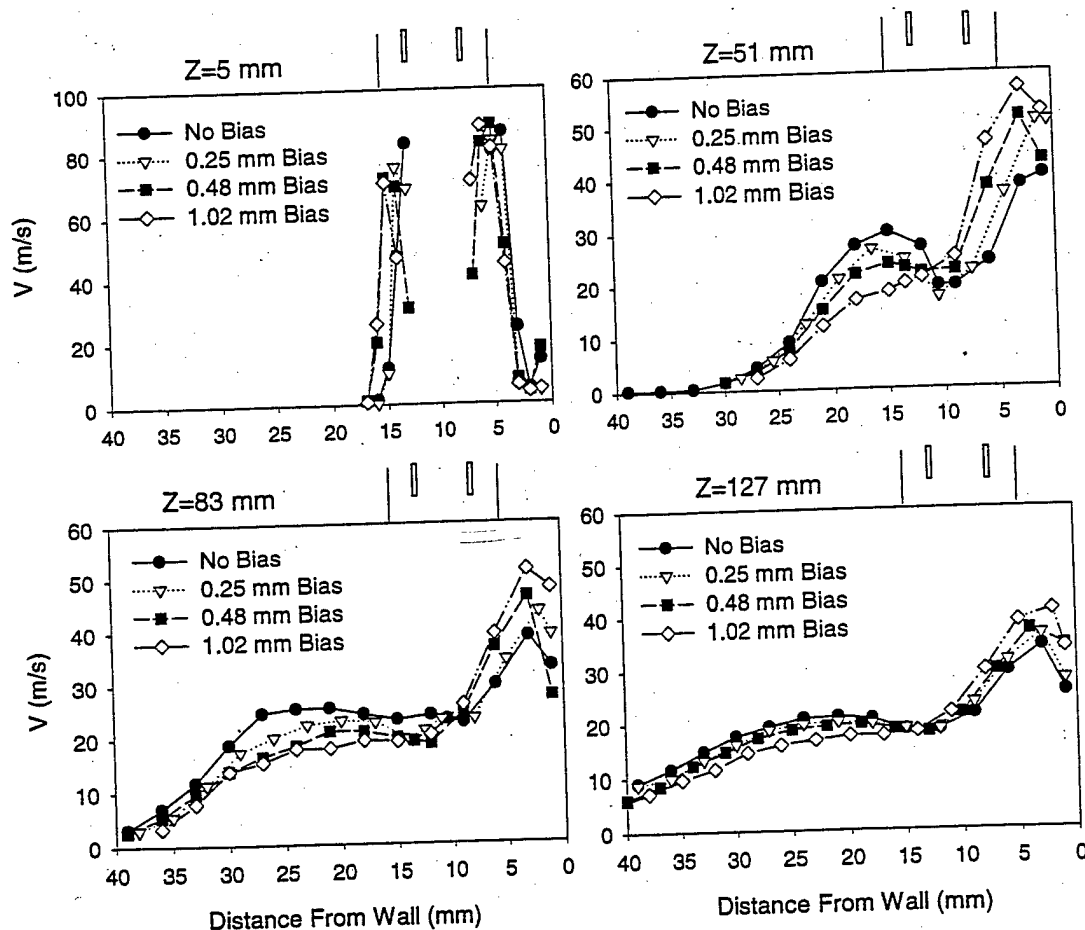


Figure 5: Gas phase axial velocity profiles versus distance from the wall at axial locations of 5, 51, 83 and 127 mm. Profiles are through the centerline of spray as defined by the LOX post and the injector is shown schematically in the plots. Test conditions listed in Table 1.

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wall side velocity must increase as the injector exit area and hence flow rate increase⁶ with bias. The effect of biasing is most prominent at the 51-mm axial location, with a decrease in relative effect as the spray evolved in time (axial distance) from the point of injection. The decrease in influence of the LOX post bias on the velocity distribution with increasing axial distance was a result of transport and mixing of the unevenly distributed gas on the wall side of the spray to the far side of the spray due to the large axial velocity gradient in the radial direction. This was the driving force behind the shift in the liquid phase away from the wall in Figure 4.

In order to calculate the liquid-to-gas mixture ratio from the liquid flux and gas phase velocity data, which were collected at different spatial resolutions, the liquid flux data was curve fit to a Gaussian profile and the mixture ratio was calculated at the data points corresponding to the gas phase velocity measurements. The mixture ratio distribution for the unbiased and biased injectors is shown in Figure 6. The shift in mixture ratio away from the wall is most prominent at the axial location of 51 mm, but persists even at the 127-mm location. The shift in mixture ratio was due to the combined effect of the shifting of the liquid flux distribution away from the wall, and the increased gas flow near the wall. The total measured mixture ratio for each run was significantly less than the injected mixture ratio of 3.25 due to entrainment of chamber gas into the spray. The amount of entrained gas increased with increasing distance from the point of injection.

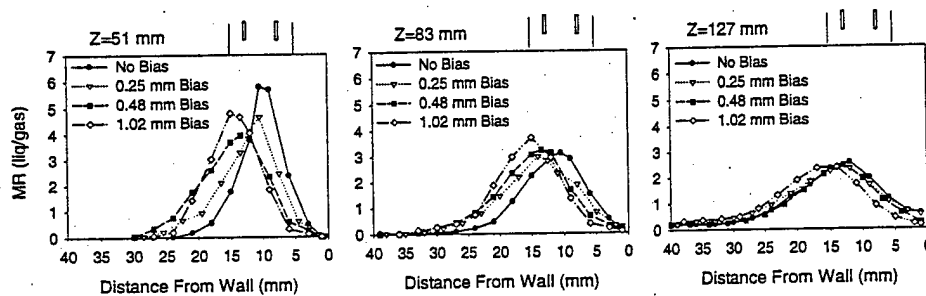


Figure 6: Mixture ratio distribution for unbiased and biased injectors at axial locations of 51, 83 and 127 mm. Injector size and location is shown on the plots. Test conditions are given in Table 1.

Heat Flux Analysis

One of the goals of the present investigation is to use the experimental cold-flow data to estimate the effects of LOX post biasing on wall heat transfer and engine performance in the SSME. Since the engine operates fuel rich, any reduction in mixture ratio near the wall might imply a decrease in hot gas temperature and heat transfer to the wall. Two approaches were used to predict relative changes in heat transfer between the unbiased and biased injector data. The first approach incorporated a flat plate turbulent heat transfer correlation (Equation 4) using the measured gas velocity and mixture ratio near the wall [4].

$$q'' = 0.0296 \text{Re}_z^{\frac{4}{5}} \text{Pr}^{\frac{1}{3}} k_g \cdot Z(T_g - T_w) \quad (\text{Eq.4})$$

$$\text{Re}_z = \frac{V_g \rho_g Z}{\mu_g}$$

Local gas temperature and transport properties were calculated using the NASA CEA chemical equilibrium code using the mixture ratio data from Fig. 6. A constant wall temperature of 600 K was assumed in the calculation for both the unbiased and biased data. The heat flux was averaged from 1 to 6 mm from the wall, which was estimated to be the extent of the thermal boundary layer at the throat of the SSME using Equation 5.

$$\delta_i = 0.37 \cdot Z \cdot \text{Re}_z^{-1/5} \quad (\text{Eq.5})$$

The average Reynolds number in the SSME combustion chamber is estimated to be about 5×10^6 which yields a boundary layer thickness of 6 mm at the throat. The calculated heat fluxes for the biased runs were expressed as a percent change from the unbiased data and are tabulated in Table 2.

Table 2: Relative change in heat transfer for biased data.

Biasing (mm)	$\Delta q''$ @Z=51 mm	$\Delta q''$ @Z=83 mm	$\Delta q''$ @Z=127 mm
0.25	-8%	-4%	-4%
0.48	-7%	-20%	-14%
1.02	-11%	-28%	-29%

It is interesting to note that the maximum reduction in heat transfer occurs further downstream with increasing LOX post bias. In the SSME the outer row of injectors contain LOX posts which are biased 0.48 mm inward. The predicted decrease in heat transfer from the cold-flow data is 7% at the 51-mm axial location, increasing to 20% then dropping off to 14% at the 127-mm axial location.

The second method of predicting heat transfer from the cold-flow data involves a manipulation of actual hot-fire test data obtained with a calorimeter test chamber. The calorimeter test data provides a profile of heat flux as a function of axial location between the injector faceplate and the chamber throat. Heat flux data obtained with unbiased injectors was adjusted by the relative change in gas velocity and mixture ratio near the wall between the biased and unbiased cold-flow data. The effect of mixture ratio and velocity on heat transfer was assumed to be similar to the previous method using a flat plate heat transfer correlation. The effect of biasing (for the 0.48-mm biased data), as measured with the cold-flow experiments was then extrapolated to the chamber throat to obtain an integrated heat load reduction of 7.1%, which agrees very well with engine test data. The main difference between these two methods of predicting heat transfer is that method 1 provides a measure of relative heat flux at several axial location, while method 2 provides a prediction of overall heat load change.

Performance Analysis

The most commonly used method of estimating the performance impact of mixture ratio nonuniformity in a rocket engine is stream-tube analysis. The assumption is that there is negligible mixing between adjacent injectors and therefore the performance of each injector can be calculated separately and summed to obtain the total engine performance, which can be measured by specific impulse. The use of stream-tube analysis to predict engine performance has been validated with a large database of experimental hot-fire data [5]. A schematic representation of stream-tube analysis is given in Figure 7 which shows that each injector element is assumed to operate over an equal area of the combustion chamber and does not mix with adjacent elements.

The SSME consists of 600 elements, 515 of which are unbiased "core" elements and 85 of which are biased "wall" elements. Each of the core elements constitutes a stream-tube, while each of the wall elements is subdivided into two sub-stream-tubes representing the wall side of the spray and the far side of the spray. The dividing line that defines the center of the spray is taken to be at the point of maximum liquid flux as measured with the cold-flow experiments. Since the shape of the liquid flux distributions for all of the runs was very similar, the relative amount of gas flow on each side of the spray was assumed to be the only factor in skewing the mixture ratio from the unbiased condition. I_s was calculated by assuming that the unbiased data represents a case of perfect mixing at the injected mixture ratio, and the biased data represents a deviation from perfection by the amount of gas flow on each side of the spray relative to the unbiased condition. Vacuum I_s was calculated using the NASA CEA chemical equilibrium code for the injected propellants. The oxidizer was LOX at 122 K, while the fuel is a mixture of 55% gaseous hydrogen and 45% water vapor by weight at approximately 800 K. Note that the mixture ratio was defined as the ratio of oxidizer to fuel, not oxygen to hydrogen. The calculated I_s as a function of mixture ratio is

provided in Figure 8. In the SSME the outer row of injectors operate at a mixture ratio of 3.0 while the core injectors operate at 3.4. The calculated I_s for each side of the spray was multiplied by the mass fraction (m_f) of propellant on each side of the spray and summed to obtain the total I_s within the stream-tube. The total I_s for the engine was calculated in a similar fashion, by summing the $I_s \cdot m_f$ of all 600

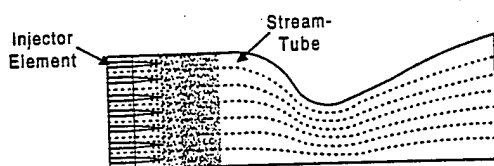


Figure 7: Schematic representation of stream-tube analysis.

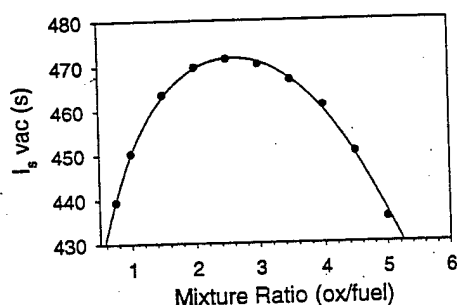


Figure 8 : Vacuum I_s versus mixture ratio for the SSME.

relative cross-sectional area of the gas annulus at the LOX post tip. The flow is divided at the center of the LOX post. This analysis does not use any of the cold flow data. It is interesting that this simple analysis agrees well with the analysis based on cold-flow data (highlighted in bold) at an axial location that decreases with increasing LOX post bias. All of the performance loss estimates for the case of 0.48-mm (SSME) show that the amount of I_s loss is very small and is probably too small to verify with full-scale engine test data.

individual stream-tubes. The calculated I_s , expressed as a change from the unbiased condition is given in Table 3 as a function of LOX post biasing at each axial location. Each axial location represents a calculation of performance assuming that that location represents the overall state of mixing in the engine. Many researchers have made direct comparisons between cold-flow and hot-fire data at equivalent axial locations. A study with gaseous oxygen and gaseous hydrogen propellants has suggested that the fraction of heat released in an engine is roughly equal to the cold-flow mixing efficiency at equivalent residence times from the point of injection [6]. For the SSME, the total chamber residence time is approximately 1 msec, which would most closely match the cold-flow data at the 51-mm location. The I_s calculations at other axial locations are provided as an estimation of the range of I_s losses that could be expected with LOX post biasing.

Also provided in the last column of Table 3 is an estimate of I_s loss from a method similar to the one just described, but where the amount of gas flow on each side of the spray is assumed to be equal to the

Table 4: I_s change from unbiased condition from cold-flow data analysis and from injector area analysis (last column).

Biasing (mm)	ΔI_s (s) @Z=51 mm	ΔI_s (s) @Z=83 mm	ΔI_s (s) @Z=127 mm	ΔI_s (s)
0.25	-0.2	-0.25	-0.13	-0.14
0.48	-0.63	-0.50	-0.27	-0.45
1.02	-2.18	-1.08	-0.87	-2.10

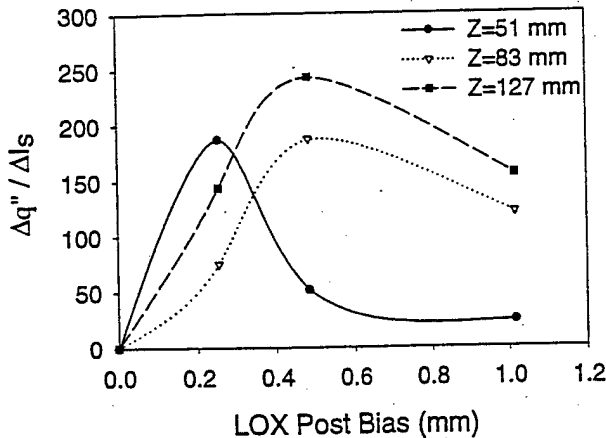


Figure 9: Percent change in heat flux normalized by the percent change in I_s as a function of LOX post bias at $Z=51$, 83 and 127 mm.

In an effort to find the optimum LOX post bias for maximizing heat transfer reduction while minimizing I_s loss, the heat transfer data from Table 2 was normalized by the percent decrease in I_s from Table 3, and is shown in Figure 9 for the three different axial locations. The peak of each curve in Fig. 9 represents the LOX post bias at which the heat transfer to I_s loss ratio is optimized. Although the 83- and 127-mm data are optimized at a bias of 0.48 mm, the 51-mm data is optimized at a bias of 0.25 mm. It is possible that the overall injector optimum operating point is somewhere between the two.

Droplet Size Measurements

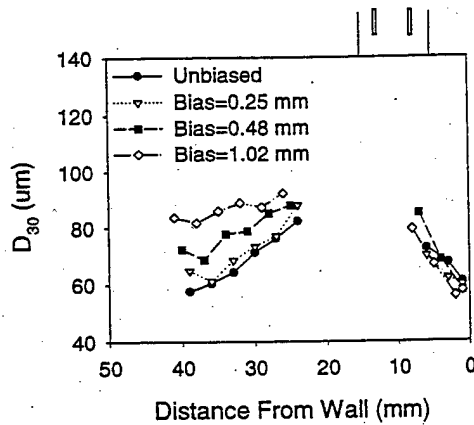


Figure 10: Volume mean diameter versus distance from wall as a function of LOX post bias at $Z=127$ mm. Test conditions from Table 1. Size and location of injector shown on plot.

Droplet size measurements were made with the PDI technique described previously. Droplet size data is presented for the axial location of 127 mm in Figure 10 in the form of the volume mean diameter, D_{30} . Droplet size data is shown only for the locations where the data validation rates were relatively high ($> 60\%$) and the PDI measured mass flux agreed relatively well with the patternator data. In the core of the spray at $Z=127$ mm, as well as with the shorter axial locations, the presence of large, nonspherical ligaments was believed to be the cause of low data validation rates. The presence of large ligaments is supported by the images in Figure 2.

Figure 10 shows an increase in D_{30} on the side of the spray away from the wall with increasing LOX post bias. This was believed to be due to the decrease in gas velocity, and hence, Weber number on this side of the spray as shown in Figure 5. There was also a corresponding

decrease in droplet size on the wall side of the spray with increasing LOX post bias.

Conclusions

The cold-flow measurements have shown a pronounced effect of LOX post biasing on the mixture ratio distribution near the wall. This was largely the result of the increased gas flow on the wall side of the injector. It is this decrease in mixture ratio, and hence combustion temperature, along with a decrease in LOX flow near the wall that provides the protection to the wall of the SSME combustion chamber.

The optimization curves in Fig. 9 provide the injector designer with information on how to design a biased injector but do not guarantee that an optimized injector will provide adequate wall protection. Maximum tolerable wall temperature might dictate that the injector be designed far from optimum. The implication for the SSME is that some reduction in the amount of biasing in the outer of injectors might recover some performance loss while still maintaining an acceptable wall temperature.

Droplet size measurements showed a decrease in droplet size near the wall with increasing LOX post bias and a corresponding increase in droplet size on the far side of the spray. The effect on droplet size is probably too small to have a measurable impact on engine performance or heat transfer.

These results will allow injector designers to better predict heat transfer and performance impact in new engines and reduce the amount of time spent in the hot-fire testing and redesign phase of an engine development program.

Nomenclature

D	droplet size (m)
h	heat transfer coefficient ($W/m^2/K$)
I_s	specific impulse
k_g	thermal conductivity ($W/m/K$)
m_f	mass fraction
MR	mixture ratio (liq/gas)
Pr	Prandtl number
q''	heat flux (W/m^2)
T_g	gas temperature (K)
T_w	wall temperature (K)
V_g	gas velocity (m/s)
Z	axial distance (from injector) (m)
ρ_l	liquid density (kg/m^3)
ρ_g	gas density (kg/m^3)
μ_g	gas viscosity ($N \cdot s/m^2$)

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